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Impact of climate change on the Hii River basin and salinity in Lake Shinji: a case study using the SWAT model and a regression curve

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Abstract:

The impacts of climate change on water resources were analysed for the Hii River basin and downstream Lake Shinji. The variation between saline and fresh water within these systems means that they encompass diverse ecosystems. Changes in evapotranspiration (ET), snow water equivalent, discharge into the basin, and lake salinity were determined for different climate scenarios. The impact of climate change on a brackish water clam found in the lake was then examined using simulated monthly variations of lake salinity and information from prior studies of the clam.

ET increased and snow water equivalent decreased for all scenarios incorporating temperature rise, particularly during the winter season. Furthermore, ET and snow water equivalent were not as sensitive to variations in precipitation and thus temperature rise was considered to be a major factor for these variables. Nevertheless, monthly discharge volume was more influenced by variation in precipitation than variations in temperature. Discharge increased during both the summer and winter season, since precipitation contributed to river discharge instead of being stored as snow pack during the winter season. The magnitudes of salinity dilutions and concentrations predicted under the climate change scenarios would not be lethal for adult clams. However, the egg-laying season of the clam would coincide with periods of strong salinity dilution in the lake. Since juveniles are less tolerant to changes in salinity, future generations of the clam may be affected and reproduction of the clam may be reduced by increasing precipitation in the future. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS evapotranspiration; hydrological sensitivity; lake salinity; rainfall variation; temperature rise

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INTRODUCTION

The aquatic environment of a brackish water lake located downstream of a river system will be significantly affected by the quantity and pattern of river flow from the basin. This implies that ecosystem diversity and function in such a lake will be influenced by changing river basin hydrology. This may in turn strongly impact small benthic animals such as *Corbicula japonica* Prime (brackish water clam) and Gobies that have low migratory ability. Changes in river basin hydrology will therefore also influence economic activities within the lake, when benthic animals in the lake are adversely impacted. Given that the aquatic environment of a brackish water lake is formed by a delicate interplay between river water and sea water, it is very important to estimate impacts to such a lake due to both gross changes in the quantity of river discharge and variation in seasonal patterns of river discharge.

One of the triggers that could cause environmental change in a river basin is global warming. Global warming is the term used to describe a gradual increase in the average temperature of the earth's atmosphere and its oceans. Global warming is considered to affect both climate and sea level. According to the Intergovernmental Panel on Climate Change (IPCC), climate change is defined as any change in climate over time, whether due to natural variability or as a result of human activity. Widespread changes in extreme temperatures have been observed over the last 50 years. Moreover, significant increases in precipitation have been observed in many places worldwide (IPCC, 2007).

Effects of changes in the energy balance of the climate system have been observed in Japan. The Japanese Islands are located in the mid-latitudes at the western edge of the North Pacific, and east of the Eurasian continent. The Japanese climate is classified as one conforming to the 'temperate zone', showing a prominent seasonal cycle (Yasunaka and Hanawa, 2006). The Japan Meteorological Agency (JMA) recently reported an increasing trend in the number of events in Japan where 1-day rainfall exceeds 200 mm during the last 100 years (1900–2000) (JMA, 2006). This trend indicates that global warming could be affecting the frequency of extreme weather events. Temperature anomalies have been increasing at a rate of approximately 1·06 °C per 100 years since 1898. Experimental predictions of future climate have been made based on an

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SRES-A2 scenario proposed by the IPCC over Japan with the Regional Climate Model (RCM20) and over the Tokyo metropolitan area and surroundings with the Urban Climate Model (UCM). These suggest that by the end of the century, the average temperature will rise by 2–3 °C from the 2000 level. In Hokkaido, an island in northern part of Japan, the increase is predicted to reach nearly 4 °C. The higher temperatures will lead to increased rainfall in most of the country, and as much as a 20% increase in western Japan, where the study area (Hii River basin) is located (JMA, 2005).

As future changes in river discharge and watershed hydrology caused by global warming are important topics for water resource management, many researchers have studied the sensitivity of stream flow and hydrological elements to climate change. Significant changes suggested include changes in flow rate and flow patterns. Numerous studies suggest that an increase or decrease in winter discharge and/or spring discharge can be caused due to seasonal shifts in the snow accumulation pattern, glacier melt runoff, and discharge of winter precipitation as opposed to the formation of snow pack being affected by global warming (e.g. Lettenmaier and Gan, 1990; Burn, 1994; Xu, 2000; Merritt *et al.*, 2006; Hagg *et al.*, 2007). Annual runoff is also increased or decreased by alterations in precipitation and evapotranspiration (ET) rates (e.g. Singh and Kumar, 1997; Huntington, 2003; Albek *et al.*, 2004; Lee and Chung, 2007). These changes are reported to influence groundwater resources and soil moisture (e.g. Arnell, 1992; Chiew *et al.*, 1995; Jyrkama and Sykes, 2007), and to increase extreme events (e.g. Pilling and Jones, 2002; Thodsen, 2007). Moreover, there is concern that future changes in river discharge and watershed hydrology will lead to the degradation of or to shifts in water resource availability in river basins (e.g. Singh and Bengtsson, 2004, 2005).

In this study, as in most other reported studies, precipitation and temperature were uniformly varied by the predicted amount over the simulation period. The hydrological response due to climate change was simulated for current climate conditions (base scenario), as well as for 18 hypothetical climate change scenarios. The 18 scenarios were different combinations of temperature rise and precipitation increase/decrease. Considering information from the JMA and IPCC, changes in temperature were set at $T + 1\,^{\circ}\mathrm{C}$, $T + 2\,^{\circ}\mathrm{C}$, $T + 3\,^{\circ}\mathrm{C}$ and those for rainfall were set to $P - 20\%$, $P - 10\%$, $P \pm 0\%$, $P + 10\%$, $P + 20\%$, $P + 30\%$ for the different climate change scenarios. Although an increase in precipitation of 30% is large compared with predictions of the JMA, this value was adopted because extreme events have increased in frequency in recent years and are likely to continue to increase in the future. Current understanding suggests that there is a possibility of temporary increases in precipitation exceeding 20% (JMA, 2005).

The objectives of this study were to understand how climate change could affect ET, snow water equivalent and discharge in the Hii River basin and salinity in Lake Shinji, and then to examine the impact of salinity variations in the lake on the clam, *Corbicula japonica* Prime, with inference from prior studies.

STUDY AREA

The Hii River basin is located in the eastern part of Shimane Prefecture, Japan (Figure 1). It covers an area of approximately 920 km^2. The length of the river from the source to the Otsu river discharge observation station, where the outlet of the whole basin is located, is approximately 63 km. Approximately 80% of the land in the basin is forest and 10% is occupied by paddy fields. Lake Shinji is located downstream of the Hii River system. Lake Shinji is the third largest brackish water lake (79·1 km^2) in Japan. Lake Shinji was designated as a Wetland of International Importance by the Ramsar Convention in November 2005. The average depth of Lake Shinji is very shallow (4·5 m). The salinity level in Lake Shinji is only one tenth that of sea water. According to Remane (1971), the classification of the lake is mesohaline. Discharge from the Hii River contributes approximately 80% of the discharge flowing into the lake. Therefore, changes in discharge pattern and quantity from the Hii River will significantly influence ecosystems and the aquatic environment in the lake. According to the Shimane Prefecture, Lake Shinji provides a crucial habitat for approximately 80 species of brackish water fish and shellfish, including a local Goby, which was first discovered in Lake Shinji. Moreover, a notable feature of this lake is the annual catch of the clam *Corbicula japonica* Prime (approximately 7000 tons). This comprises approximately 94% of total harvest (all species) from the lake and approximately 40% of the national total catch of *Corbicula japonica* Prime. It is the largest catch in Japan. According to statistical data from the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) in 2002, total sales of *Corbicula japonica* Prime from Lake Shinji came to approximately 40 million dollars. Thus, the fishery is one of the most important economic concerns in the prefecture.

METHODOLOGY

This study is divided into three steps as shown in Figure 2. The first was to simulate water discharge using a hydrological model. The second was estimation of climate change impact on the hydrological balance of the Hii River basin using determined parameter values. The third was estimation of changes in salinity in Lake Shinji using a regression curve and simulated water discharge for different climate change scenarios. The combinations of precipitation and temperature variations are shown in Table I. The regression curve was determined from the observed relationship between lake salinity and river discharge. Thus salinity derived from the regression curve was modified by the water balance between direct precipitation to the lake and evaporation from the lake

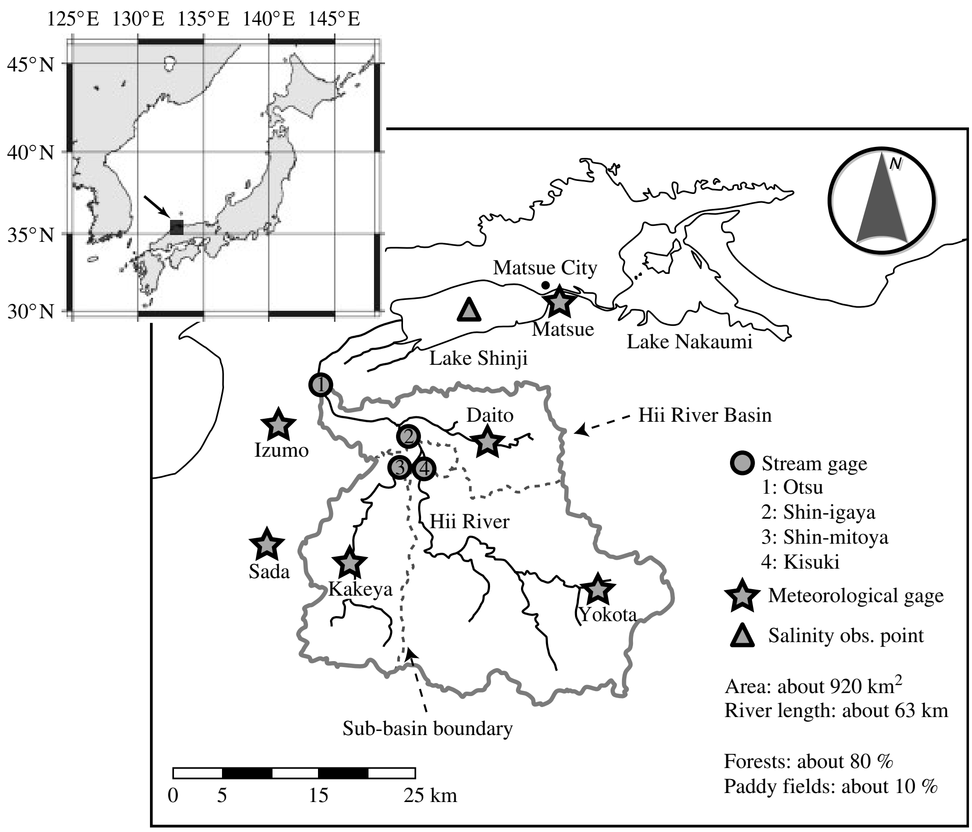

Figure 1. Location of Hii River basin and salinity observation point in Lake Shinji

Table I. Combinations of precipitation and temperature change scenarios

Variation of precipitation	Variation of temperature		
	1 °C	2 °C	3 °C
−20%	$P - 20\%\ T + 1\,°C$	$P - 20\%\ T + 2\,°C$	$P - 20\%\ T + 3\,°C$
−10%	$P - 10\%\ T + 1\,°C$	P − 10% T + 2 °C	$P - 10\%\ T + 3\,°C$
±0%	$T + 1\,°C$	$T + 2\,°C$	$T + 3\,°C$
+10%	$P + 10\%\ T + 1\,°C$	$P + 10\%\ T + 2\,°C$	$P + 10\%\ T + 3\,°C$
+20%	$P + 20\%\ T + 1\,°C$	$P + 20\%\ T + 2\,°C$	$P + 20\%\ T + 3\,°C$
+30%	$P + 30\%\ T + 1\,°C$	$P + 30\%\ T + 2\,°C$	$P + 30\%\ T + 3\,°C$

surface. Finally, based on the results, the effect of climate change on *Corbicula japonica* Prime was examined using information from prior studies.

Hydrological components such as ET, snow water equivalent and discharge were simulated using the Soil and Water Assessment Tool (SWAT) model. The model was applied to the Hii River basin from 1985 to 2005 using a daily time step. The year 1985 was treated as the warming period during the model simulation, and the results for the remaining 20 years were used for the hydrological response analysis. The Hii River basin was divided into four sub-basins according to the locations of stream gauges within the basin (Otsu, Shin-igaya, Shin-mitoya, and Kisuki). The parameters were calibrated at the four stream gauges using data from 1993 to 1996, and validated using data from 1986 to 1992 and from 1997 to 2005. The data set from 1993 to 1996 was used for calibration as it had a higher quality of discharge data (Table II). In addition, actual rice yields were used as another indicator of model performance and compared with statistical information and simulated rice yields.

Brief description of the SWAT model

The SWAT model was selected for this study because many researchers worldwide have validated the model and confirmed its performance and algorithms (Govender

Table II. The number of missing data in river discharge at each station

Sub-basin number and name	1986–1992	1993–1996	1997–2005
Sub 1 (Otsu)	137	21	17
Sub 2 (Shin-igaya)	14	3	16
Sub 3 (Shin-mitoya)	156	3	4
Sub 4 (Kisuki)	16	0	42

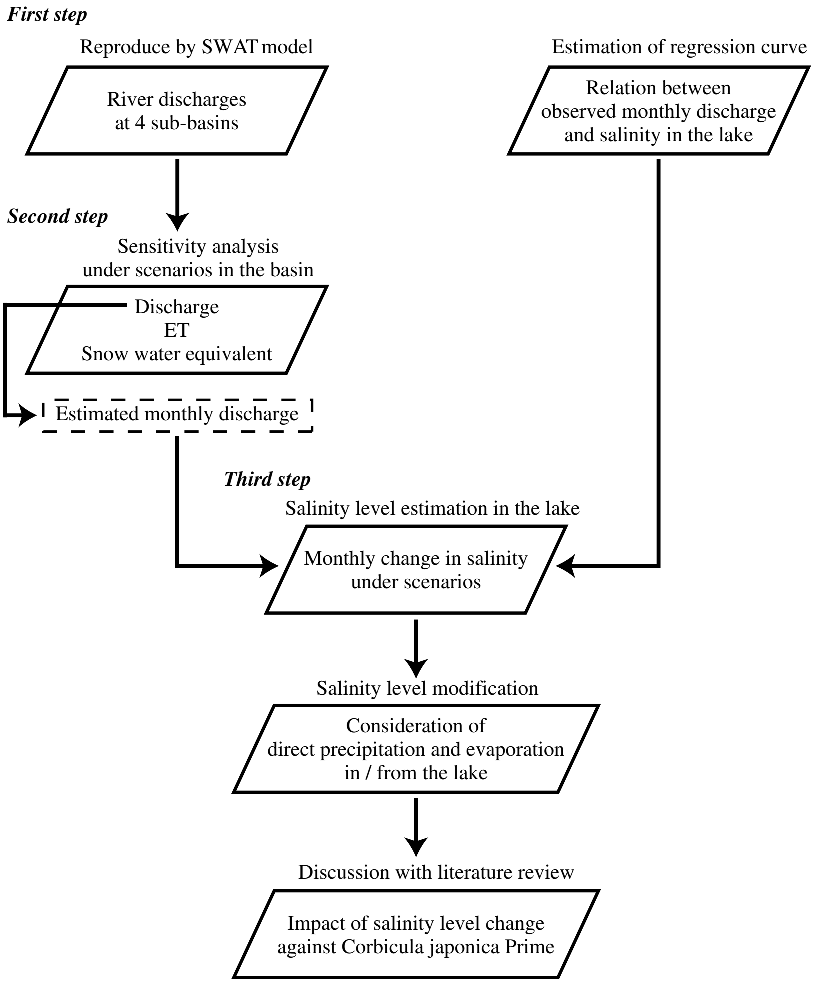

Figure 2. Flow chart for the study

and Everson, 2005; Bärlund *et al*., 2007; Huang *et al*., 2007; Lee and Chung, 2007; Wu and Johnston, 2007). In addition, climate change impacts have previously been simulated using SWAT, including simulations of: the effects of increased atmospheric CO_2 concentrations on plant development and transpiration; changes in climatic inputs on plant growth and stream flow (Gassman *et al*., 2007); and the severity of droughts and intensity of floods in various parts of India (Gosain *et al*., 2006).

The model is a physically based continuous time hydrological model and is provided with an ArcView Geographic Information System (GIS) interface (Di Luzio *et al*., 2004). It was designed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex basins with varying soil type, land use, and management conditions over long periods of time (Arnold *et al*., 1998).

The model is largely driven by the hydrological component. The hydrological processes are divided into two phases: the land phase, which controls the quantity of water and sediment and the nutrient load input into receiving waters, and the water routing phase, which simulates movement through the channel network. The model considers both natural sources (e.g. mineralization of organic matter and N fixation) and anthropogenic contributions (fertilizers, manures, and point sources) as nutrient inputs. The model delineates watersheds into sub-basins interconnected by a stream network. Each sub-basin is divided further into hydrological response units (HRUs) based on unique soil/land class characteristics without any specified location in the sub-basin. Flow, sediment, and nutrient loading from each HRU in a sub-basin are summed, and the resulting loads are then routed through channels, ponds, and reservoirs to the watershed outlet (Arnold *et al*., 2001).

A single growth model in SWAT is used for simulating all plants based on a simplification of the Erosion-Productivity Impact Calculator (EPIC) crop model (Williams *et al*., 1984). Phenological development of the crop is based on daily heat unit accumulation. The model estimates evaporation from soils and plants separately. Potential ET can be calculated using either the Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestley and Taylor, 1972), or Hargreaves method (Hargreaves and Samani, 1985) depending on data availability. In the study, the potential ET was computed using the Penman-Monteith method, based on observed daily air temperature, relative humidity, solar radiation, and wind speed data. Potential soil water evaporation was estimated as a function of the potential ET and leaf area index (area of plant leaves relative to soil surface area).

The model includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. The weather generator first independently generates precipitation for the day. The maximum temperature, minimum temperature, solar radiation, and relative humidity are then generated based on the presence or absence of rain for that day. Finally, the wind speed is generated independently.

Input data description

The SWAT model requires meteorological data, such as daily precipitation, maximum and minimum air temperature, wind speed, relative humidity, and solar radiation. Additional spatial data sets including a digital elevation model (DEM) and maps of land cover and soil type are required. As there were some inconsistencies and missing climate data, the WXGEN weather generator included in the SWAT model was used.

Meteorological data were obtained from the JMA (http://www.jma.go.jp/jma/index.html). A number of gauges measuring precipitation, air temperature, and wind speed are variously positioned in and around the basin. Five gauges for precipitation and three gauges for air temperature and wind speed were chosen. However, there was no gauge used for monitoring the relative humidity data within the basin. Therefore, relative humidity data recorded in Matsue City (located approximately 30 km away) was used instead. Solar radiation was estimated since there was no gauge monitoring the solar radiation within the basin. Solar radiation data were calculated using the Angstrom formula (FAO, 1998). Parameter values were determined from solar radiation data measured at Shimane University (http://www.ipc.shimane-u.ac.jp/weather/i/home.html) and the actual sunshine duration within the basin obtained from the JMA. For all of the meteorological data the percentage of missing data was very low, with a maximum 0·14% (11 days) during 21 years (7671 days). The mean values of the climatic data recorded at each gauge are shown in Table III.

Daily discharge data for the four monitoring stations (Otsu, Shin-igaya, Shin-mitoya, and Kisuki) were obtained from the Izumo River Office in the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

DEM data were prepared with a 50-m grid created from a 1 : 25 000 topographic map provided by the Japanese Geographical Survey Institute.

Land use data included categories, such as paddy field, upland field, orchard, bare land, forest, water, and others. The data were obtained from the National Land Information Office in the MLIT (http://nlftp.mlit.go.jp/). Area and ratio of major land use types in each sub-basin are shown in Table IV. Forest area varied spatially from 59 (Sub 2) to 87% (Sub 4) and the area of paddy fields from 9 (Sub 3) to 18% (Sub 2). The area of upland fields and orchards were small and occupied <5% of the land use in all sub-basins.

Soil data were copied from GIS soil map obtained from a 1 : 500 000 Fundamental Land Classification Survey prepared by the MLIT (http://tochi.mlit.go.jp/tockok/index.htm). Soil type was categorized into 10 groups of 14 soils: dystric rhegosols, fluvic gleysols, gleysols, haplic andosols, helvic acrisols, humic cambisols, lithosols, ochric cambisols, rhodic acrisols, and vitric andosols.

Table III. Average annual precipitation and climatic variables from 1985 to 2005 at each gauge

Gauge name	EL (m)	Annual precipitation (mm)	Maximum air temperature (°C)	Minimun air temperature (°C)	Wind speed (m/s)	Relative humidity (%)	Solar radiation (calculated) (MJ/m^2)
Matsue	16·9	—	—	—	—	75·6 (10·0)	—
Izumo	20	1726	18·9 (8·3)	10·3 (8·1)	2·2 (1·2)	—	11·1 (7·5)
Daito	56	1778	—	—	—	—	—
Sada	100	2072	—	—	—	—	—
Kakeya	215	2046	18·0 (9·0)	8·8 (8·3)	1·3 (0·7)	—	—
Yokota	369	1765	17·2 (9·3)	7·5 (8·8)	1·2 (0·7)	—	—

The values in parenthesis indicate standard deviation.

Table IV. Area and ratio of major land use in each sub-basin

Sub-basin number and name	Drainage area (km^2)	Sub-basin			
		Sub-basin area (km^2)	Forests (%)	Rice fields (%)	Upland fields and orchards (%)
Sub 1 (Otsu)	919·8	189·3	74	16	3
Sub 2 (Shin-igaya)	730·5	19·5	59	18	5
Sub 3 (Shin-mitoya)	203·1	203·1	86	9	3
Sub 4 (Kisuki)	507·9	507·9	87	10	2

These values were obtained from a digital elevation map and a land use GIS map. The values of drainage area at the Otsu observation station were slightly different from the values reported by the Ministry of Land, Infrastructure, Transport and Tourism (911·4 km^2).

Observed rice yield was calculated using rice production and harvested area data obtained from MAFF (http://www.tdb.maff.go.jp/toukei/toukei).

Model performance evaluation

The SWAT model was calibrated and validated using the observed discharge data. The coefficient of determination (R^2) and Nash-Sutcliffe index (*NSI*) (Nash and Sutcliffe, 1970) were used to evaluate the model performance. The R^2 value is an indicator of the strength of the relationship between the observed and simulated values. The *NSI* value indicates how well the plot of the observed versus simulated values fits the 1 : 1 line. The range of the *NSI* value is between $-\infty$ and 1. If the R^2 and *NSI* values are less than or very close to zero, the model performance is considered to be unacceptable or poor. If the values are equal to one, then the model prediction is considered to be perfect.

$$NSI = 1{\cdot}0 - \left(\sum_{i=1}^{n}(Q_{obs,i} - Q_{cal,i})^2 \Big/ \sum_{i=1}^{n}(Q_{obs,i} - \overline{Q}_{obs})^2\right) \quad (1)$$

where n, the number of registered discharge data; $Q_{\mathrm{obs},i}$, the observed discharge at time i; and $Q_{\mathrm{cal},i}$, the simulated discharge at time i.

Relationship between lake salinity and river discharge

In this study, a regression curve was used to estimate the impact of changes in river flow discharge on patterns on the salinity in the lake. The regression curve was developed using data for salinity and discharge from December 1988 to November 1998 (Figure 3). The chloride level of the lake was measured monthly by the MLIT at a central location (35°27′1″ N, 132°57′36″ E). Recordings were made at different depths: near the surface (<1 m from water surface), mid-depth, and at the lake bottom (1 m above the lake bed). Chloride ion concentration was determined by titration with silver nitrate (Mohr's method). The chloride ion concentration was converted into salinity (salinity = 1·80655 Cl; Fofonoff, 1985). Salinity calculated for samples taken at the lake bottom were used for the regression curve, since the aim was to estimate the impact of salinity changes on benthic animals. Discharge data from the Otsu station were recorded on a daily basis by the MLIT. However, since the data for chloride concentration were recorded monthly, monthly values for flow data were also generated. The regression curve is shown in Equation (2). Chloride ion concentration was measured at the beginning of each month. Thus, it was considered that the salinity on the observed day would be affected by the river flow during the previous month. For this reason, salinity for the current month and discharge for the previous month were compared in the regression curve. It should be noted that unit (‰) is called 'permille' and is a unit of proportion, which is equal to 0·001 or one part per thousand. This unit indicates the salinity level of water.

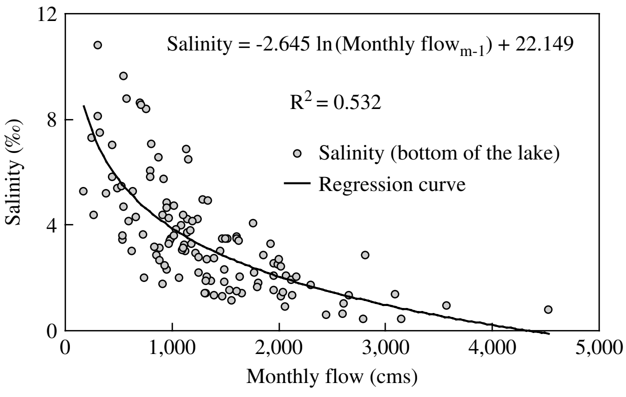

Figure 3. Relationship between monthly flow at Otsu and salinity at the observation point in Lake Shinji. This regression curve was developed using data for the decade from December 1988 to November 1998

$$Salinity\_rc\ (‰) = -2{\cdot}645\ \ln\,(D_{m-1}) + 22{\cdot}149 \quad (2)$$

where D, monthly flow (cms); and m, month.

Modification of the lake salinity as estimated from the regression curve

Lake salinity, estimated using the regression curve, was further modified to account for the impact of climate change on direct precipitation into the lake and evaporation from the water surface of the lake. Difference in direct precipitation (ΔP) was calculated using the monthly mean precipitation at the Izumo gauge from 1986 to 2005 (base scenario) and modified according to each scenario for precipitation variation. Potential evaporation (E_{p}) was estimated by the Food and Agricultural Organization of the United Nations (FAO) Penman-Monteith method (Allen *et al*., 1998). This method is currently widely used and can be considered standard. The method uses standard climatic data that can be easily measured or derived from commonly measured data. For this analysis, measured data such as actual sunshine duration, temperature, air pressure, and wind speed collected from 1986 to 2005 were employed. In addition, necessary data such as net radiation and vapour pressure were estimated. The value of the albedo was set to 0·06 for the water surface (Payne, 1972; Gao *et al*., 2006). The change in E_{p} (ΔE_{P}) was calculated using the E_{p} of the base scenario and the modified E_{p} based on each climate change scenario. The current data for air pressure, sunshine duration, and wind speed were used for this analysis; however, it should be noted that these values may change in the future.

The water depth of Lake Shinji for each scenario was estimated using the monthly water depth, ΔP, and ΔE_{p}. This depth was used for modifying the estimated salinity using the regression curve. The base scenario for water depth was calculated using the monthly measured water depth collected by the MLIT from 1985 to 2003 at five observation points in Lake Shinji. The modified salinity in the lake for each climate change scenario was thus calculated using Equations (3) through (5).

$$Salinity\_modified(‰) = Ls/(WDe \times A\_shinji) \quad (3)$$

$$(Ls)_m = Salinity\_rc \times (WDb)_m \times A\_shinji \quad (4)$$

$$(WDe)_m = (WDb)_m + (\Delta P - \Delta E_p)_{m-1} \quad (5)$$

where *Ls*, salinity load (kg); *WDe*, estimated water depth (m); *WDb*, base scenario water depth (m); *A_shinji*, area of the lake (m^2); ΔE_p, difference in potential evaporation between climate change scenarios and base scenario (m); and ΔP, difference in precipitation between climate change scenarios and base scenario (m).

RESULTS AND DISCUSSION

Reproducibility of river discharge at the four discharge observation stations

A sensitivity analysis was performed using a Latin hypercube, a one-at-a-time method (van Griensven *et al.*, 2006). Then an autocalibration process was executed using the shuffled complex evolution (SCE) algorithm (Duan *et al.*, 1992). Although the sensitivity analysis indicated that daily flow was most sensitive to only 10 input parameters, 27 parameters were varied for the calibration procedure in order to achieve the highest model performance for the climate change scenarios. The most sensitive ten parameters with final calibrated values are shown in Table V. The simulated and observed flow statistics for calibration and validation are shown in Table VI. The best fit for daily stream flow during calibration was on average $R^2 = 0{\cdot}79$ and $NSI = 0{\cdot}78$. During validation the average best fit was $R^2 = 0{\cdot}67$ and $NSI = 0{\cdot}64$.

Simulated and observed daily discharge is shown in Figure 4. It was considered that both the results of calibration and validation at each sub-basin represented the fluctuations in discharge relatively well, although some peaks were overestimated or underestimated. In particular, on October 20, 2004, the basin was struck by a typhoon No. 23 (JMA) and the observed precipitation was approximately 150 mm at the Yokota rain gauge (a total of approximately 200 mm for 2 days), 120 mm at the Kakeya rain gauge (a total of 165 mm for 2 days), and 100 mm at the Daito rain gauge (a total of 150 mm for 3 days). Therefore, the simulated discharge on and around those days at all the sub-basins was high, particularly at sub-basin 4. These heavy rains and the spatial variability are one of the reasons for the low statistical values of *NSI* and R^2 during validation periods. Nevertheless, the daily flow statistics found in this study are in line with previous SWAT studies (Gassman *et al.*, 2007).

Reproducibility of the average rice yield in basin

Estimated rice yields were verified with actual rice yields obtained from a statistical report on agriculture, forestry, and fisheries (Figure 5). To obtain reasonable rice yields from the model, irrigation and fertilizer management data were input based on local schedules for rice production. The rice yields recorded in the statistical report were collected in units of a town or a village. Therefore, the area which each statistical value

Table V. The most sensitive ten parameters and the final calibrated values of the parameters

Ranking	Parameter name		Final calibrated value (s)
1	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	9·59
2	RCHRG_DP	Deep aquifer percolation fraction	0·003
3	SOL_AWC*	Available water capacity of the soil layer (mm H_2O/mm soil)	0·039–0·189
4	CN2*	Initial SCS runoff curve number for moisture condition II	37–90
5	SLOPE*	Average slope steepness (m/m)	0·09–0·12
6	CANMX	Maximum canopy storage (mm H_2O)	4·65
7	ESCO	Soil evaporation compensation factor	0·65
8	SOL_K* (first layer)	Saturated hydraulic conductivity (mm/h)	0·5–131·5
9	GW_REVAP	Groundwater 'revap' coefficient	0·34
10	SOL_Z* (first layer)	Depth from soil surface to bottom of layer (mm)	60·0–171·6

The parameter values marked by '*' vary depending on soil types, soil layers, and/or land use classifications.

Table VI. Simulated versus observed daily statistics for Hii River discharge calibration and validation

Sub-basin number and name	Calibration period		Validation periods			
	1993–1995		1986–1992		1996–2005	
	R^2	*NSI*	R^2	*NSI*	R^2	*NSI*
Sub 1 (Otsu)	0·76	0·76	0·61	0·55	0·61	0·58
Sub 2 (Shin-igaya)	0·80	0·78	0·66	0·54	0·71	0·69
Sub 3 (Shin-mitoya)	0·80	0·79	0·68	0·67	0·71	0·71
Sub 4 (Kisuki)	0·80	0·80	0·72	0·71	0·66	0·63

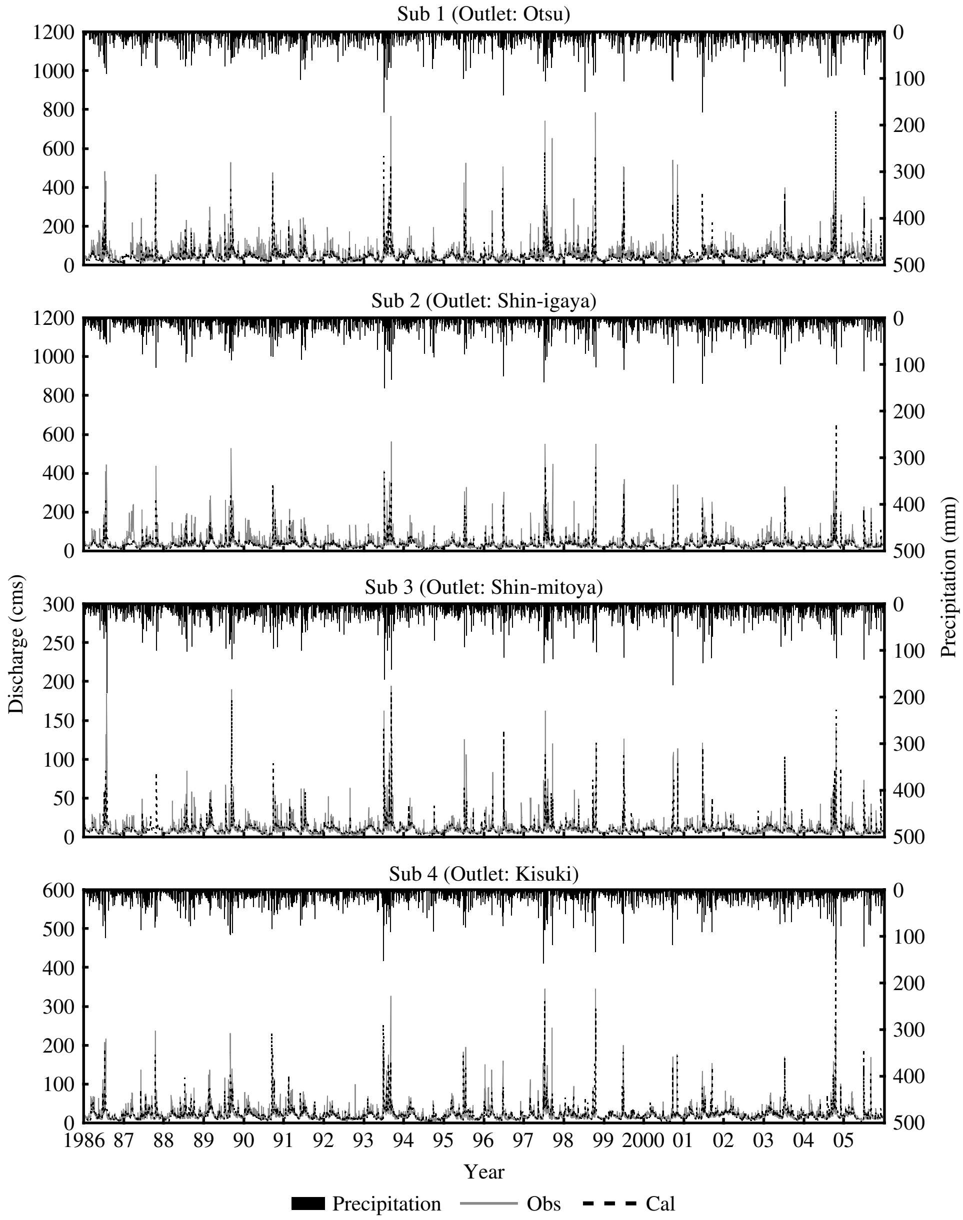

Figure 4. Simulated and observed daily discharge (calibration: 1993–1995, validation: 1986–1992 and 1996–2005)

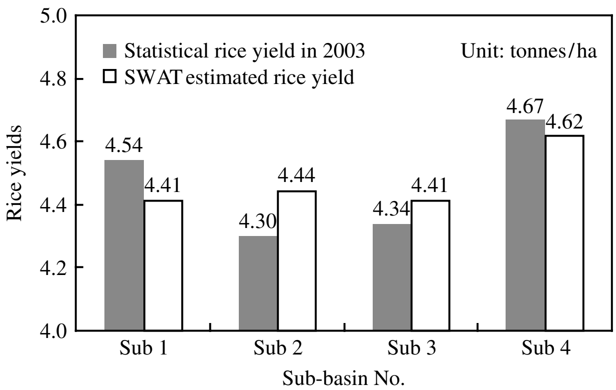

Figure 5. Estimated and statistical rice yields in the basin

represented was not perfectly equivalent to each sub-basin area in the model. The estimated yields for each sub-basin were compared with the statistical data for the town or village that dominated that sub-basin. When more than two dominant values existed for one sub-basin, the average value was used for comparison. The overall average value for statistical and estimated rice yields were 4·46 and 4·47 tons per hectare, respectively. This suggests that rice yield was reproduced accurately by the model when compared with the statistical data for rice yields in the towns and villages in the basin.

Relative impact of climate change on monthly flow discharge at Otsu observation station

The mean monthly flow discharge at the Otsu observation station for all climate scenarios is shown in Figure 6. In this basin, runoff is somewhat more sensitive to changes in precipitation than to changes in temperature, as found by Nash and Gleick (1991). Although in theory, in glacier basins, changes in runoff are reported to be more sensitive to changes in temperature than to changes

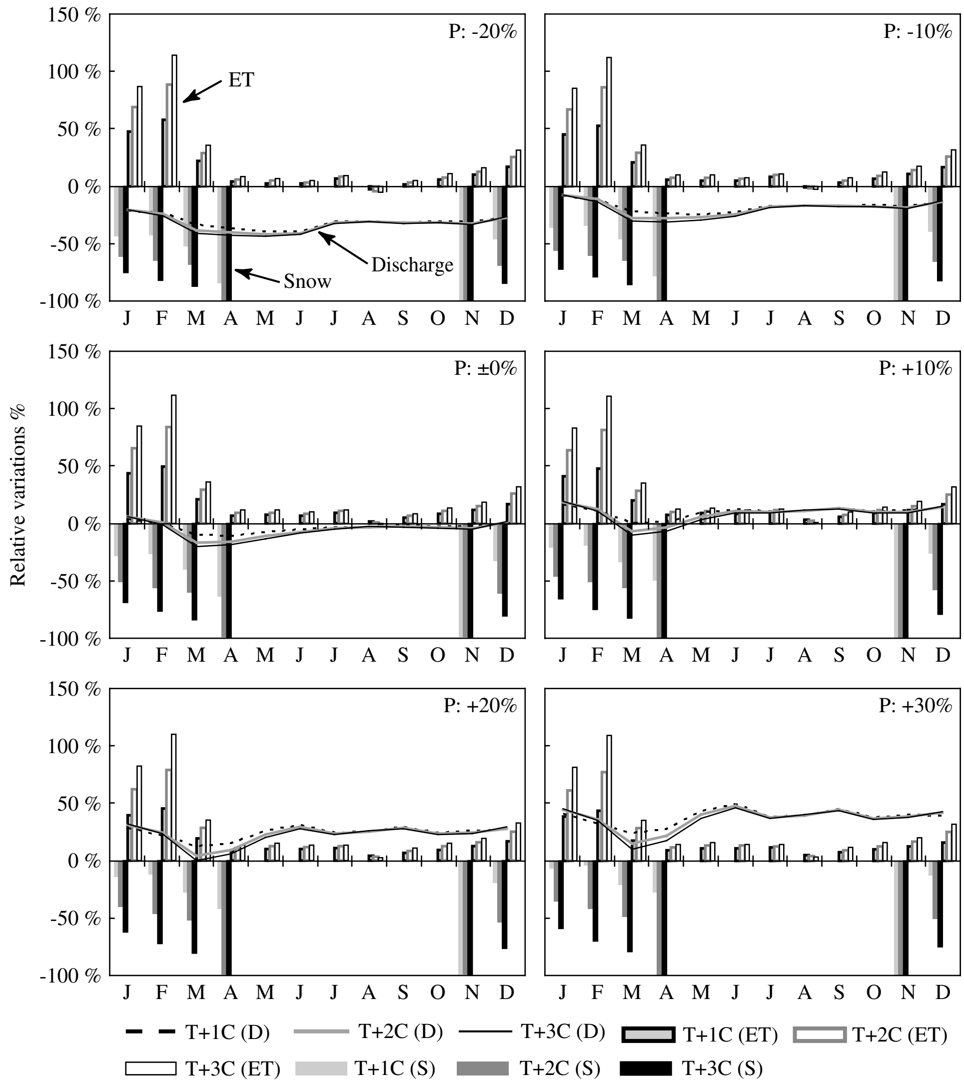

Figure 6. Relative variations of snow water equivalent (S), evapotranspiration (ET), and discharge (D) in Hii River basin between the climate change scenarios and the base scenario

in rainfall (Singh *et al*., 2006). From the results, it seemed that the variation in river discharge would be larger than the proportion variation in precipitation. This trend was evident in scenarios with decreasing precipitation. For example, when precipitation decreased by 20%, river discharge decreased by more than 30% on average over a year and more than 40% on average between March and June. In the worst case scenario of precipitation decrease ($\Delta T = +3\,^{\circ}C$ and $\Delta P = -20\%$), river discharge in May decreases by nearly half (-44%) of the base scenario. Even in other months, the average decrease in river discharge ranged from 21 (January) to 33% (September and November). Similar trends were shown in the 10% precipitation decrease scenario. A multiplicative effect occurred, as precipitation decreased and temperature rose, the effect on discharge was compounded.

For precipitation increase scenarios, river discharge increased in most cases as expected. Average annual river discharge increased by 23 ($P + 20\%$) to 37% ($P + 30\%$). In the worst case scenario of precipitation increase ($\Delta T = +1\,^{\circ}C$ and $\Delta P = +30\%$), river discharge in June increased by 50%. Interestingly, with precipitation increasing by 10%, river discharge was predicted to decrease in March and April. Overall, a precipitation increase of 10% resulted on average in annual discharge increases of $<$10%.

Discharge significantly increased not only in the summer season but also in the winter season. This was because precipitation was discharged as river water instead of being stored as snowpack during the winter season. Discharge increased by 45% in January and by 43% in December for the scenario $\Delta T = +3\,^{\circ}C$ and $\Delta P = +30\%$. Increasing temperature from 1 to 3 °C caused discharge to increase in January and December. However, in all other months, discharge decreased with increased temperature. Overall, the average annual discharge decreased by a few percent with an increase in temperature from 1 to 3 °C.

Relative impact of climate change on monthly snow water equivalent in basin

A marked reduction in the average snow water equivalent for all the alternative scenarios was observed, because of the increased temperature during winter

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(Figure 6). The maximum reduction in snow water equivalent was observed for the combined scenarios where temperature increased by 3 °C. The snow water equivalent decreased by 100% in November for all scenarios and decreased by 100% in April for scenarios with $\Delta T = +2\,°C$ and $\Delta T = +3\,°C$. In other words, the snow-cover-free period increased from 6 months (May to October) to 8 months (April to November) with a temperature increase of 2 °C over current climate conditions. In other combined scenarios where the temperature increased by 1 and 2 °C, for all precipitation changes, a progressive reduction in the average snow water equivalent was observed from precipitation increase to decrease scenarios. Mean annual values of snow water equivalent reduced from 29 ($\Delta T = +1\,°C$) to 81% ($\Delta T = +3\,°C$) for the scenario $\Delta P = +30\%$; from 49 ($\Delta T = +1\,°C$) to 85% ($\Delta T = +3\,°C$) for the scenario of only temperature increase; and from 62 ($\Delta T = +1\,°C$) to 89% ($\Delta T = +3\,°C$) for the scenario $\Delta P = -20\%$.

Relative impact of climate change on monthly ET in basin

As expected, ET increased under climate scenarios of temperature increase, especially during the winter season in January and February (Figure 6). A significant increase was not observed during other months. As temperature is considered to be one of the limiting factors for ET in the winter season, it was expected that ET would increase significantly, particularly during the winter season. It was estimated that actual ET increased approximately 1·5 times relative to base conditions in January and February, when temperature increased by 1 °C. When temperature increased by 3 °C, ET nearly doubled in January and more than doubled in February. Moreover, it was revealed that variation in precipitation did not notably affect the actual ET variations for all scenarios. Despite changes in the seasonal distribution of the actual ET, the change in annual ET was relatively small. On an average annual basis, the actual ET increased from approximately 15 ($\Delta T = +1\,°C$) to 30% ($\Delta T = +3\,°C$).

Uncertainty in the salinity estimation using the regression curve

Currently, lake water salinity is affected not only by the discharge from the rivers but also by meteorological influences such as direct precipitation into the lake and evaporation from the surface of the lake. The regression curve prepared for the current situation already includes the direct influence of these meteorological phenomena on the lake. However, the direct meteorological influences of variation in precipitation and temperature increase cannot be expressed by this regression curve for the simulated future climate scenarios. In other words, it is not enough to consider the future variation of salinity in the lake due to discharge. Therefore, a simplified analysis for estimating the uncertainty related to precipitation into the lake and evaporation from the surface of the lake was attempted using the results shown in Figure 7. This figure shows the relationship between the monthly ΔP directly incident on the lake and ΔE_p from the surface of the lake (A), and the variation in the monthly mean water depth of the lake (B). The effects of these phenomena for each scenario were determined using an annual water balance, as shown in Table VII. In the precipitation decrease and temperature increase scenario, it was clear that the salinity in Lake Shinji increased beyond the values estimated by the regression curve because of the reduction in direct precipitation to the lake and the increase in evaporation from the water surface due to temperature increase. The largest magnitude of salinity increase occurred for the scenario $\Delta T = +3\,°C$ and $\Delta P = -20\%$. According to the monthly calculation for this modification, salinity increased by 1 to 2% in every month compared with the results for the regression curve. In the scenario of only temperature increase, since only ΔE_p increased and precipitation did not change in association with the present condition, the salinity increased slightly more than the value estimated by the regression curve. According to the monthly calculation, salinity increased by approximately 1% in several months compared with the results for the regression curve. On the other hand, in the case of precipitation and temperature increase, ΔP increased more than ΔE_p, except at $\Delta P = +10\%$. This indicates that the salinity in Lake Shinji will be reduced more than the values estimated by the regression curve. The greatest degree of salinity dilution occurred for the scenario $\Delta T = +1\,°C$ and $\Delta P = +30\%$. According to the monthly calculation, salinity was diluted by approximately 1% in several months compared with the results for the regression curve, except in the scenario of $\Delta P = +10\%$. For $\Delta P = +10\%$ scenario, no clear difference was observed. Although an increase in the sea level

Table VII. Variation of yearly water balance (In: ΔP, Out: ΔE_p) on the surface of Lake Shinji to complement the uncertainty of salinity differences by scenarios

Unit: mm

$\Delta P - \Delta E_p$	ΔP ($P - 20\%$)	ΔP ($P - 10\%$)	ΔP ($P \pm 0\%$)	ΔP ($P + 10\%$)	ΔP ($P + 20\%$)	ΔP ($P + 30\%$)
ΔE_p ($T + 1\,°C$)	−512·9	−342·2	−171·5	−0·8	170·0	340·7
ΔE_p ($T + 2\,°C$)	−540·3	−369·6	−198·9	−28·1	142·6	313·3
ΔE_p ($T + 3\,°C$)	−567·7	−397·0	−226·3	−55·6	115·1	285·8

Positive values indicate that the salinity in Lake Shinji will dilute more than the current estimation by regression curve by dominant ΔP to the surface of Lake Shinji. On the other hand, negative values indicate that the salinity will increase more than the current estimation by the dominant ΔE_p from the surface of Lake Shinji.

Base case (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation	116.3	101.3	121.6	97.4	151.3	192.2	241.8	124.6	198.6	121.3	120.9	120.0
E_p	28.9	33.7	56.2	82.9	100.6	94.8	105.5	115.0	82.1	63.7	41.5	31.9

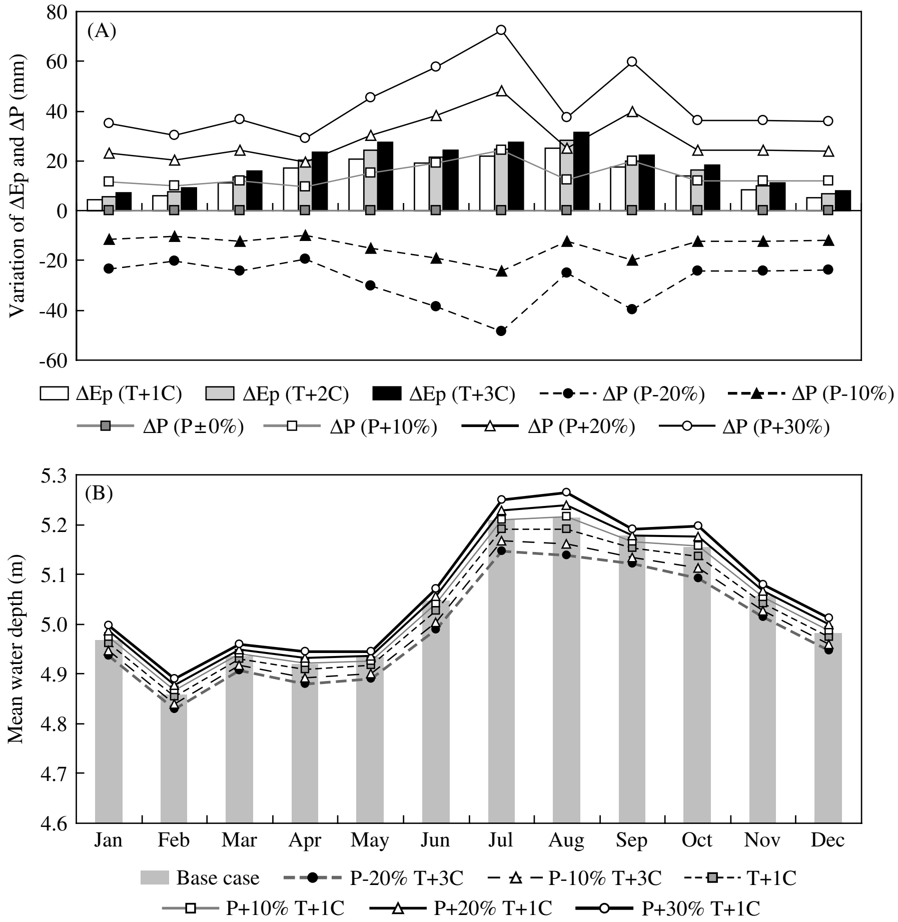

Figure 7. Relationship between estimated monthly ΔP fall to Lake Shinji and monthly delta potential evaporation (ΔE_p) from the surface of Lake Shinji for the climate change scenarios (A), and variation of estimated monthly water depth in Lake Shinji (B)

due to global warming is predicted by the IPCC (2007) and it is considered that this phenomenon will affect the salinity of Lake Shinji, this was ignored in this study. Discharge from other rivers into the lake will also be affected by global warming. All of these factors remain as additional uncertainties.

Relative impact of climate change on salinity in Lake Shinji

Variations in the mean monthly discharge and modified salinity are shown in Figure 8. As expected, salinity in the lake reflected monthly variations in river discharge. The magnitude of salinity variations was dependent on variation in precipitation while temperature increase did not significantly influence lake salinity. When river discharge decreased due to precipitation decrease, salinity levels increased. Contrary, when river discharge increased because of precipitation increase, salinity levels decreased. When precipitation decreased by 20%, salinity levels increased throughout the year and relative variations in salinity increased by 51% in April and by 47% in August. For the mean annual values, the maximum salinity increase was 33% ($\Delta T = +3\,^{\circ}$C). When precipitation increased by 30%, salinity levels decreased during the year, with a maximum decrease of 37% in August and 33% in October. For average annual salinity values, the maximum salinity reduction was 24% ($\Delta T = +1\,^{\circ}$C). Salinities during spring and summer seasons from April to August increased more than precipitation for the precipitation decrease scenarios. On the other hand, in the precipitation increase scenarios, maximum variations of salinity were comparable to precipitation variation. In the precipitation increase scenarios, the trend was for salinity to start decreasing in May and continue decreasing until August. Low salinity levels persisted throughout the winter until March.

The effect of climate change on Corbicula japonica Prime

One of the goals of this research was to analyze the impact of climate change on salinity in Lake Shinji and the impact of salinity variations in the lake on *Corbicula japonica* Prime. From the results of this study, the maximum average annual salinity increase (33%) occurred

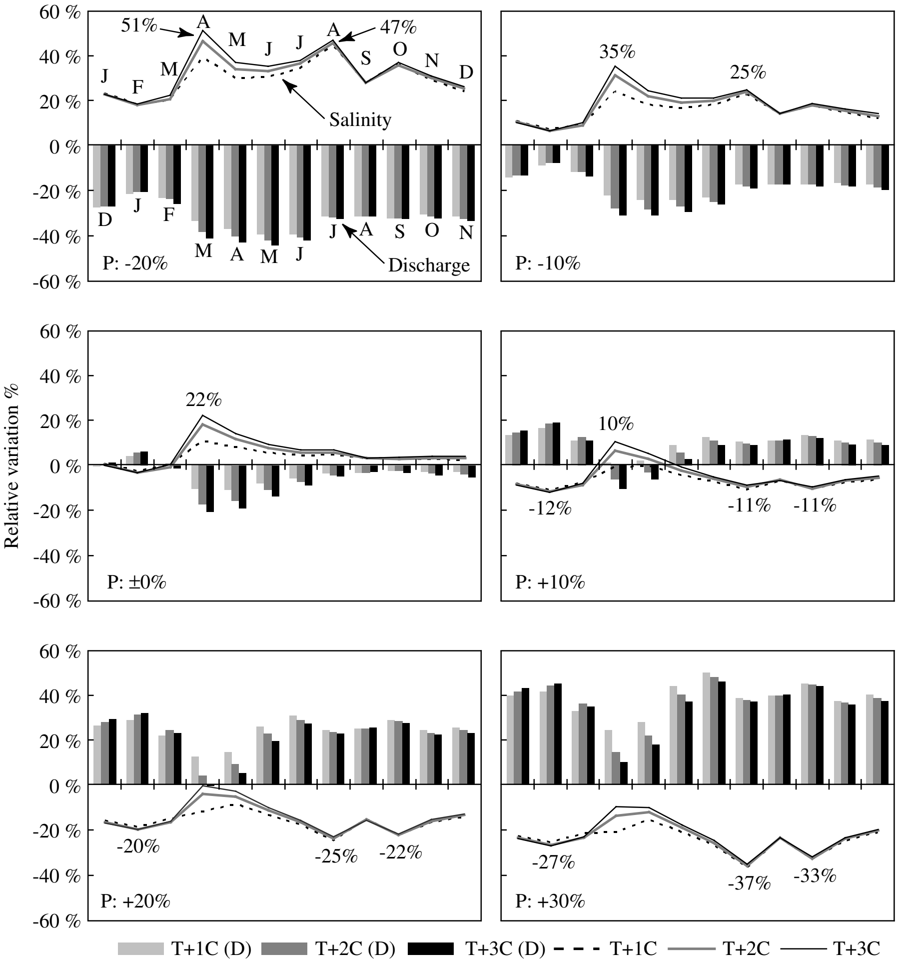

Figure 8. Relative variations in salinity in Lake Shinji between the climate change scenarios and the base scenario from the regression curve

with a precipitation decrease and temperature increase scenario. Conversely, average annual salinity decreased by 24% with a precipitation and average annual temperature increase scenario. An important characteristic of *Corbicula japonica* Prime is the species' tolerance to variable salinity (Remane, 1971; Mashiko, 1981; Kunii *et al*., 1993). *Corbicula japonica* Prime is considered to be euryhaline (Nakamura *et al*., 1996a). Researchers have reported suitable salinities for adults of *Corbicula japonica* Prime, caught at the Kiso River estuarine, ranging from 3·5 to 10·5‰(Tanaka, 1984b). Moreover, salinities ranging from 1·5 to 22‰were not lethal for adults of *Corbicula japonica* Prime caught at Lake Shinji (Nakamura *et al*., 1996a). Given this tolerance, fluctuations in salinity in the lake caused by climate change are not considered to be a critical factor for the survival of adults of *Corbicula japonica* Prime. Nevertheless, the survival salinity thresholds for fry of euryhaline invertebrates would be narrower than those for adults, and fry of euryhaline invertebrates are commonly intolerant of salinity fluctuations (Lockwood, 1976). Thus, seasonal changes in salinity were examined to determine impacts on the species life cycle. According to the IPCC, there is a high possibility of increasing precipitation in this region and seasonal salinity dilution will be a problem, particularly during August and October under the precipitation increase scenario. Asahina (1941) and Tanaka (1984a) reported that eggs of *Corbicula japonica* Prime and post-larval stages cannot survive in fresh water. Furthermore, the lower boundary of salinity for egg cleavage has been reported as 3·12‰(Asahina, 1941). The egg release season for *Corbicula japonica* Prime occurs from the end of March to the beginning of November (Kawashima and Goto, 1988), with a peak from July to September (Asahina, 1941; Kawashima and Goto, 1988). The dilution in salinity levels due to increases in river discharge and direct precipitation into the lake during the summer season may thus affect the production of *Corbicula japonica* Prime. In addition, water temperature also influences salinity tolerance and the survival threshold of *Corbicula japonica* Prime (Nakamura *et al*., 1996a,b). Thus, it will be necessary to consider the compounded impact of water temperature fluctuation in the Lake Shinji on *Corbicula japonica* Prime in the future.

CONCLUSIONS

To understand and predict climate effects on the Hii River basin and downstream Lake Shinji, the SWAT model and a regression curve were employed. The findings are summarized as follows:

- River discharge was estimated to decrease with precipitation decrease and to increase with precipitation increase. The magnitude of discharge fluctuation was additionally influenced by temperature variations impacting on the ET rate.
- With the precipitation decrease scenario, the maximum reduction in the discharge was 44% in May for the scenario $\Delta T = +3\,^{\circ}\mathrm{C}$ and $\Delta P = -20\%$. In the 20% precipitation increase scenario, discharge increased in every month except March ($\Delta T = +3\,^{\circ}\mathrm{C}$). The maximum increase in the discharge was 50% in June for the scenario $\Delta T = +1\,^{\circ}\mathrm{C}$ and $\Delta P = +30\%$.
- The snow-cover-free period increased from 6 to 8 months in scenarios with an increase in temperature $>2\,^{\circ}\mathrm{C}$.
- Actual ET increased under the climate scenarios of temperature increase, particularly during the winter season from January and February. Annual variations in actual ET were much smaller. Thus, global warming had a much greater impact on the hydrological balance during the winter season.
- Salinity increased throughout the year, particularly during April and August for scenarios with a decrease in precipitation. The maximum increase in the annual average salinity was 33% ($\Delta T = +3\,^{\circ}\mathrm{C}$ and $\Delta P = -20\%$). With only temperature increase, salinity increased in most months with large increases in April and May. The maximum increase in the annual average salinity was 6% for the scenario $\Delta T = +3\,^{\circ}\mathrm{C}$. A maximum salinity reduction of 24% was predicted for mean annual values ($\Delta T = +1\,^{\circ}\mathrm{C}$ and $\Delta P = +30\%$).
- With increased precipitation during the summer season keeping lake salinity levels low, production of *Corbicula japonica* Prime may be reduced, as eggs of *Corbicula japonica* Prime and post-larval stages cannot survive in fresh water (the lower limit of salinity for egg cleavage has been reported as 3·12‰). Thus, impacts of global warming may damage economic activities in the region.

This study suggests that impacts of river hydrology on downstream lake salinity can be an important factor for benthic animals within the lake such as Gobies and *Corbicula japonica* Prime. Furthermore, these species may also be affected by changes in nutrient input patterns from the river basin. This topic demands more detailed analyses of direct and compound effects including salinity, nutrient input, and water temperature variation in order to comprehend sustainable utilization and maintenance of this aquatic environment.

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